EVALUATION OF ALUMINUM SULFATE FOR PHOSPHORUS CONTROL IN EUTROPHIC LAKES

by

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I. Introduction

Eutrophication is the enrichment of lakes and reservoirs with plant nutrients and with sediments, and these together may lead to greatly increased biological production and decreased volume. Eutrophication is one of the most serious and widespread water quality problems in the world. Systems which are eutrophic commonly exhibit extensive areas of macrophytes, "blooms" of nuisance algae which lower water transparency and add poor taste and odor, oxygen depletion which may eliminate certain fish from the system, and an abundance of nuisance species (e.g. carp). The consequences of these and other symptoms may include recreational impairment, increased industrial or municipal water treatment costs, and lowered property values in residential developments. Nearly all urban lakes in Ohio are eutrophic, and most of our reservoirs may become so with the next decade.

Eutrophication is caused, in some instances, by a sharp increase in sediment-nutrient income from sewage effluents, erosion from land development, or drainage from agricultural or livestock operations. In many other cases, lakes and reservoirs may lie in naturally rich soils so that income to the lake is sufficiently rich to promote eutrophication. Most often, a combination of cultural and geological influences bring about the eutrophic state.

Lakes and reservoirs vary in their potential to become eutrophic. This was clearly described by Vollenweider (1968, 1976), Dillon and Rigler (1976), and others, who showed that lakes with high mean depth and rapid flushing rates required very high rates of nutrient income in order to bring about sufficient increases in nutrient concentration to support algal blooms, while other lakes, such as the very common shallow, slow flushing systems, may become eutrophic easily. Also, there may be a positive feedback loop in some eutrophic lakes (Cooke et al. 1977) wherein "internal loading" of nutrients from decomposition and from activities of fish and macrophytes in littoral areas, and from reduced sediments, may stimulate plant production and thereby further increase the release of bound nutrients in sediments. Eutrophic lakes may thus recycle materials far more extensively than non-eutrophic ones, thus maintaining high productivity.

Restoration of some eutrophic lakes may be accomplished by diversion of point sources of nutrient income, particularly if nutrient-poor streams are the principle sources of water (e.g. Edmondson, 1970). In many other cases, where nutrients enter from multiple and diverse sources, including non-point sources, diversion is essential to stop or retard further deterioration, but may not lead to rapid recovery since nutrients and sediments continue to enter the lake (Cooke et al. 1978). Further, internal loading may maintain nutrient concentration in the water well in excess of that which would be predicted by the washout characteristics of the lake (e.g. Larsen et al. 1975). Or, as in the more usual case, macrophytes may be a more serious problem than algae and their production may not be controlled by a lowering of nutrient concentration.

Many lake restoration techniques have been proposed (Peterson et al. 1974), but very few have been subjected to a rigorous experimental evaluation to assess the amount of recovery. One of these techniques, termed "nutrient inactivation," is meant to stop or greatly retard sediment-nutrient release by binding an essential plant element so that it is not released from sediments under reducing conditions. The target element of this method is phosphorus since it has a sedimentary biogeochemical cycle, and because it most often is the element controlling production in lakes (Schindler, 1974). It is assumed with this lake rehabilitation technique that the principle source of internal phosphorus loading is the reduced sediment overlain by hypolimnetic water, where phosphorus is returned to the epilimnion by seiches and vertical entrainment, as described by Mortimer (1971, 1974).

Aluminum sulfate has been used as a phosphorus inactivant in several lakes, but in these studies the methods of application varied widely (dry or dissolved alum, surface or deep application, time of application), there was little or no basis for dose, and follow-up studies after application were often meager. The hypolimnetic applications of 100 tons of liquid alum to West Twin Lake, and 10 tons to Dollar Lake, which form the basis of this report, are apparently the first experimental examination of this lake rehabilitation technique wherein the alum was specifically applied to reduced hypolimnetic sediments, the dosage based upon toxicity data and aluminum chemistry, and the effect monitored and compared to a similar untreated downstream lake.

The purpose of this report is to summarize the response of the East and West Twin lakes to septic tank diversion, and to the alum treatment of West Twin in 1975, with an emphasis on the state of the lakes in 1978. The report also includes a description of the response of the pilot treatment lake, Dollar Lake, to the 1974 alum applications.

II. Watershed Description

The Twin Lakes Watershed has been fully described (Cooke and Kennedy 1970; Kennedy, 1978; Cooke et al. 1978), and these features are summarized in Table 1. Dollar Lake (Table 1), also found in the Twin Lakes Watershed (Figure 1) has been described by Dexter (1950), Cooke and Kennedy (1970), Ottersen (1974), and espcially by Kennedy (1978).

The three lakes are dimictic, second-class lakes (terminology of Hutchinson, 1957), freezing in December, thawing in March, and stratifying thermally by mid-April. Destratification occurs in November.

There are about 380 homes in the watershed, 40 of them around Dollar Lake. Prior to 1972, all homes were serviced with septic tanks, and obtained water from deep wells. In 1972, septic tank drainage was diverted to a small treatment plant and the effluent directed into the nearby Cuyahoga River. Before sewage

Table 1

Limnological Features of Twin and Dollar Lakes[1]

latitude-longitude 41°12' north; 81°21' west area of watershed (ha) 334.5 (including lakes)

	West Twin	East Twin	Dollar
area (ha)	34.02	26.88	2.22
max. length (km)	0.65	0.85	0.20
max. width (km)	0.60	0.50	0.13
volume (m^3)	14.99×10^5	13.50×10^5	0.86×10^5
max. depth (m)	11.50	12.00	7.50
mean depth (m)	4.34	5.03	3.89

[1]data from Cooke et al. (1978) and Kennedy (1978).

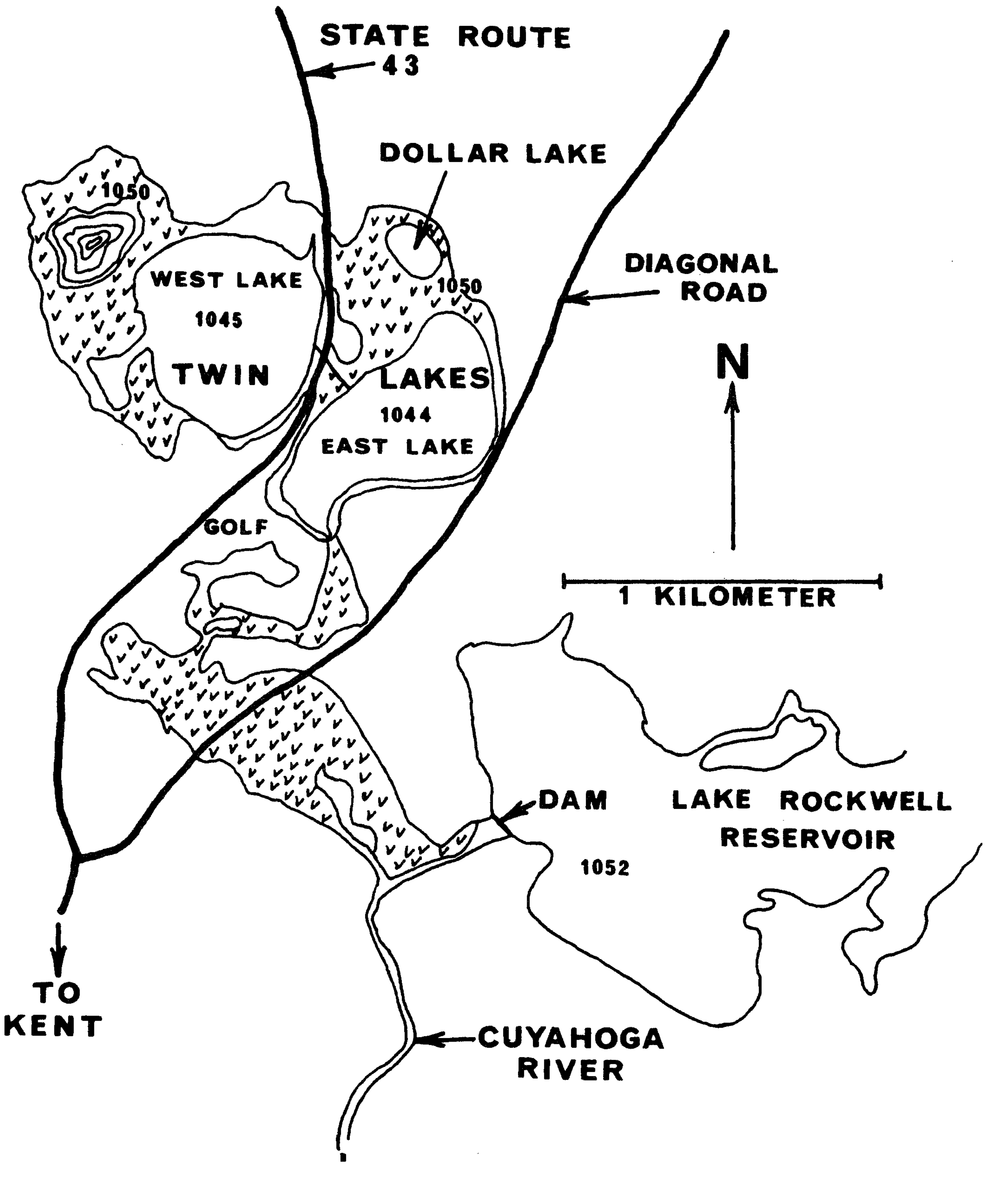


FIGURE 1a. Map of the Twin Lakes - Kent region of Northeastern Ohio.

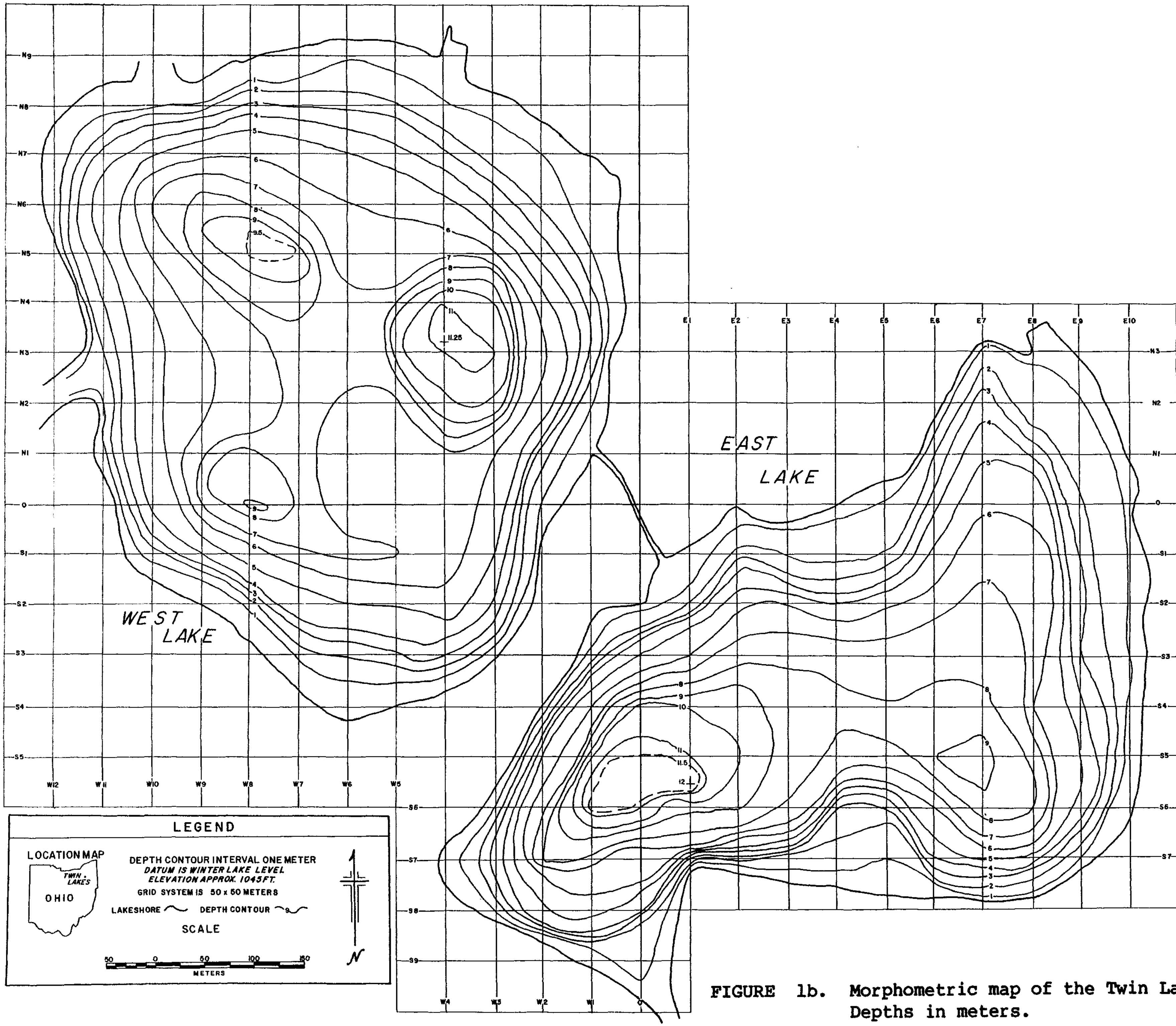
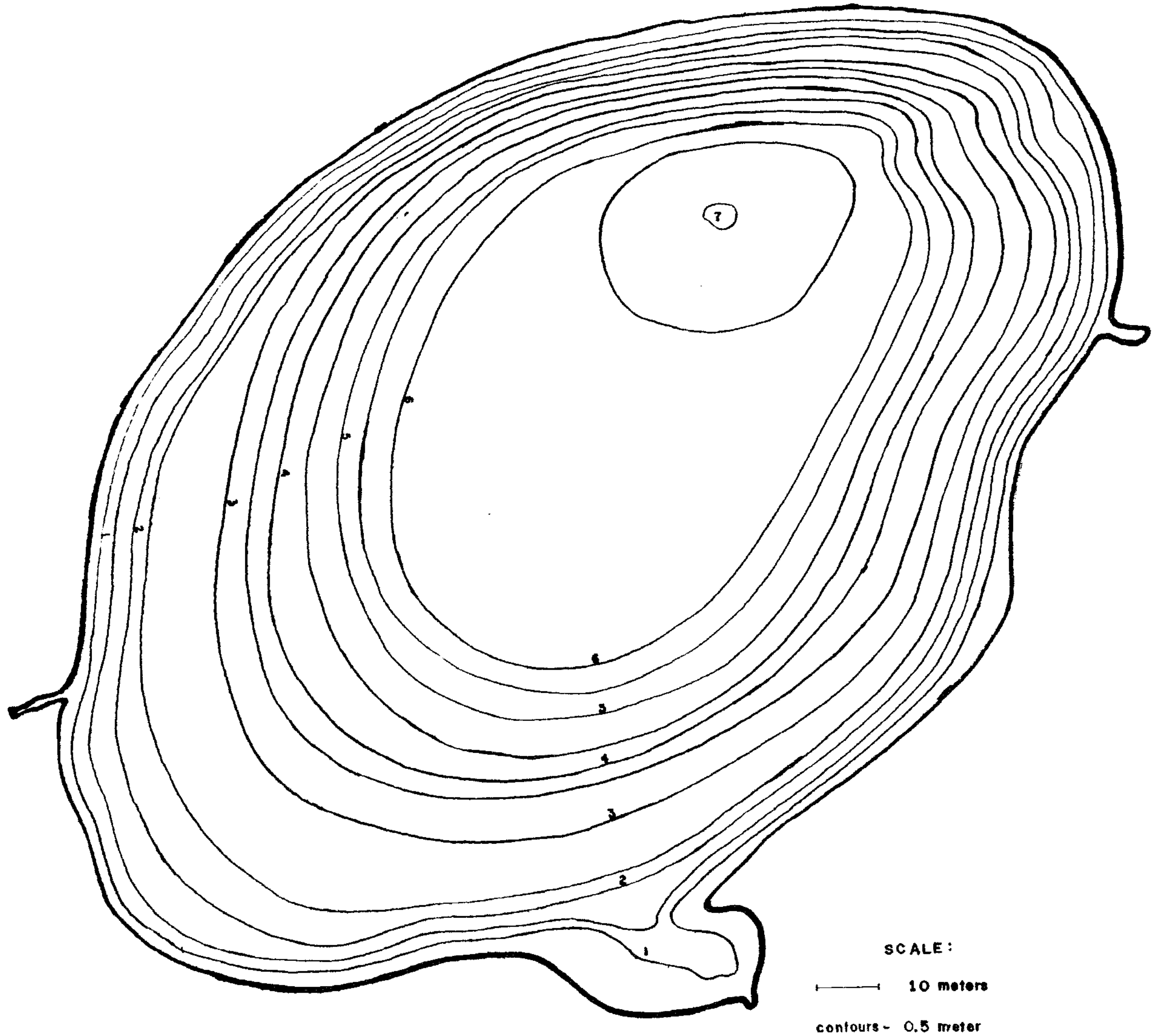


FIGURE 1b. Morphometric map of the Twin Lakes. Depths in meters.



DOLLAR LAKE

FIGURE 1c. Morphometric map of Dollar Lake. Depth in meters.

diversion, the lakes had been closed to contact recreation due to excessive fecal coliforms.

The lakes exhibited symptoms common to eutrophic or enriched lakes in the years before (Heinz, 1971) and just after diversion (Cooke et al. 1978). Dissolved oxygen is rapidly depleted from hypolimnetic waters, and partially depleted after ice formation. Plant nutrients are found in high concentrations, and the plankton flora is dominated by blue-green algae. About 25% of the lake surface areas of East and West Twin are considered littoral, and are dominated by nuisance macrophytes, such as species of *Potamogeton*, *Najas*, *Ceratophyllum*, *Elodea*, and *Chara* (Rogers, 1974). The littoral area of Dollar Lake is small. The dominant fish in all lakes are members of the Centrarchidae.

Dollar Lake is a eutrophic, alkaline bog lake with an extensive marsh surrounding it. There is a *Sphaghum* shelf around its margin, with species of *Typha*, *Larix*, *Acer*, and *Alnus*. In contrast, the adjacent Twin Lakes are surrounded with homes and lawns which extend to the shore. The marsh of Dollar Lake is continuous with the northwest shore of East Twin.

The water budgets of the lakes differ. Dollar Lake receives water from storm drainage, small springs which do not flow except during lengthy precipitation periods, a perennial spring, and groundwater. It has no outlet, although Ottersen (1974) believed that during the high water periods water flowed into East Twin through the marsh. A water budget for the lake has not been constructed, but it is probable that the lake is a seepage lake, with a comparatively long water residence time.

West Twin receives about half of its annual water supply from small springs and outflow from upland lakes and about half from groundwater. The lake discharges into East Twin. This discharge usually constitutes at least half of the water income to East Twin, although in 1974-76, groundwater accounted for up to 70% of East's income. East Twin then discharges water from the watershed to a marsh, which drains into the Cuyahoga River. Annual water residence time (V/Q_0) for West Twin has varied from 0.97 to 1.60 years, and for East Twin, has varied from 0.45 to 0.70 years. Further details of the water budgets of the lakes are given in Cooke et al. (1978).

III. Materials and Methods

Sampling of the Twin Lakes began in 1971 and was continuous at weekly intervals through September, 1976. No samples were taken in 1977. Weekly sampling resumed in April, 1978 and continued through mid-September, 1978. A few samples were taken in 1969-70 (Heinz, 1971). Dollar Lake was sampled occasionally in 1968-70, then weekly from 1973-1976, and again during summer, 1978. All samples from the three lakes were taken at a single lake station over the deepest portion.

A. Chemical-Physical Measurements

Temperature (YSI resistance thermometer), dissolved oxygen (azide modification of the Winkler method) and phosphorus forms (USEPA, 1971) were sampled at meter intervals. All water chemistry samples were placed in acid-rinsed polyethylene bottles and analysis begun within an hour of collection. The phosphorus content of the lakes was obtained by multiplying the mean concentration of total phosphorus between each one meter interval by the volume of that interval, and then summing the products. Volumes are given in Cooke and Kennedy (1970) and Cooke et al. (1978).

Alkalinity (titration of whole lake water with 0.02N H_2SO_4 to pH 4.5), pH (Corning Model 12 meter), conductance (YSI Model 31 Conductivity Bridge), sulfate (turbidometrically; Hach Chemical Company), and aluminum (colorimetrically, Hach Chemical Company) were usually measured from two samples from the epilimnion,one from the metalimnion, and two from the hypolimnion. Transparency was measured with a 20 CM alternating black-white quadrant Secchi Disc. ph was averaged by obtaining the mean anti-log.

B. Biological Measurements

Chlorophyll a was measured by filtering known volumes of surface water through a Whatman GF/A glass filter and extracting with 90% $MgCO_3$-buffered acetone in a tissue grinder according to the procedure of Long and Cooke (1971). Pigment concentration was computed from the trichromatic equation of Strickland and Parsons (1968) without acid correction. Samples were filtered and extracted in a darkened room.

Phytoplankton cell volume was measured by filtering a 25 ml. sample of surface water through a 0.45μ Millipore filter. The procedure of McNabb (1960) was used, and cell volumes were estimated from their approximation to various geometric shapes.

Zooplankton were sampled by combining two vertical hauls of a #25 net. Samples taken in 1976 and 1978 from the Twin Lakes were compared to the 1969-1970 samples of Heinz (1971), obtained in a nearly identical way, through the use of the diversity indices of Shannon and Weaver (1949),

$$H' = -\Sigma P_i \ln P_i \qquad (1)$$

where: P_i is the percent importance of the i^{th} species

and Simpson (1949),

$$D = 1-\Sigma P_i^2 \qquad (2)$$

and by the Coefficient of Similarity of Pinkham and Pearson (1976),

$$B = 1/k \sum_{i=1}^{k} \frac{\min (X_{ia} \quad X_{ib})}{\max (X_{ia} \quad X_{ib})}$$

Where: x_{ia} and x_{ib} are the numbers in the i^{th} taxon in samples a and b respectively and k is the number of comparisons of different taxa in the two samples.

The Pinkham and Pearson (1976) index describes species co-occurrence and abundance simultaneously and will have a value of 1.0 when compared samples are identical in abundance and species occurrence and 0.0 when the samples are completely dissimilar.

The population density of each zooplankton species was summed for the 17 samples of each lake in 1969, the 13 samples in 1976, and the 16 samples in 1978. These aggregated samples were considered to best illustrate the relationship between species number and abundance, rather than the abrupt changes which occur from week to week over a summer.

The trophic state changes due to diversion and aluminum sulfate application were quantitatively expressed, using the Carlson (1977) Trophic State Index (TSI). The index is a continuous scale, based on algal biomass and its relationship to Secchi Disc transparency and to correlations of chlorophyll and total phosphorus.

C. Water-Nutrient Budget Measurements

The hydrologic equilibrium equation was used to describe the water balance of the watershed at all times during the study. Details are described in Cooke et al. (1978). In 1978, the water-phosphorus budget was measured from May through mid-September. Rates of surface water inflow and outflow were measured with a Marsh-McBirney model 201 flow meter approximately four times weekly. Flow rates for days of no measurement were determined by linear interpolation. Water samples for phosphorus concentration were obtained at the time of measurement. Since summer 1978 was extremely dry,daily or continuous measurements of flow and concentration were not made. Rainfall was measured in Kent, approximately 8 km. south, and lake evaporation data were obtained from the Agricultural Research Service in Coshocton, Ohio, 160 km south of the watershed. The mean annual (1972-1976) phosphorus concentration in precipitation, 25 μg/l, was used since no 1978 samples could be collected. Change in water storage was measured at the time of stream sampling by the change in water level in each lake relative to a fixed mark on a steel pier girder.

Groundwater inflow was obtained by assigning all residual water income from the hydrologic equilbrium to groundwater. Four alternative techniques have been attempted at Twin Lakes, and it was found that the solution of the hydrologic equation gave values very similar to those obtained with seepage meters and lakeside wells plus a flow net (Cooke et al. 1978). In-lake piezometers and the thermal gradient methods gave rates one order of magnitude lower and higher, respectively. A phosphorus concentration of 86 and 56 µgP/l, the long-term (1972-76) mean groundwater concentration for West and East Twin Lakes respectively was used to estimate the import of phosphorus from this source.

D. Measurement of Internal Phosphorus Loading

The release of phosphorus from anoxic hypolimnetic sediments was hypothesized to be the principle internal source of phosphorus to the epilimnion, and was therefore the target of the aluminum sulfate application.

The rate of internal phosphorus loading was obtained by solution of the mass balance equation (Cooke et al. 1977):

$$P_{lake} = (P_i - P_o) \pm P_{int} \qquad (4)$$

where:

P_{lake} = change in lake phosphorus content from spring low to summer high

P_i = phosphorus income

P_o = phosphorus losses via outflow

P_{int} = phosphorus gained (net release) or lost (net sedimentation)

E. Aluminum Sulfate Application

A maximum dose of aluminum sulfate, defined as that dose above which residual dissolved aluminum exceeds 50µgAl/l, was applied by barges to the hypolimnetic of Dollar Lake in July, 1974 (10 tons) and West Twin in July, 1975 (100 tons), with the purpose of placing a "blanket" of aluminum hydroxide over the phosphorus-rich reduced sediments in order to prevent or retard phosphorus release. A small amount of alum was also added to the epilimnion of Dollar Lake (Kennedy, 1978) but none was added to any lake zone except the hypolimnion in West Twin. Previously, in situ experiments with polyethylene columns and seepage meters had shown that this dosage was very effective in preventing phosphorus release, and reports in the literature as well as our own toxicity studies had shown that the dose would be non-toxic to fish. These studies are reviewed in Cooke et al. (1978) and Kennedy (1978).

Details of the application procedure, the physico-chemical reactions of aluminum sulfate with water, the results of preliminary testing, and a step-by-step method for obtaining dose for any lake are presented in detail in Kennedy (1978) and Cooke et al. (1978). The treatment of these two lakes appears to be the first in which the basis for dosage was defined, and in which the only object of the experiment was to place as much aluminum hydroxide on the sediments as possible without developing a toxic level of residual dissolved aluminum, for the purpose of preventing phosphorus release. All earlier experiments with alum appeared to have no basis for dose, and were directed towards phosphorus removal from the water column. The Twin Lakes experiment was directed exclusively at long-term control of phosphorus release from reduced hypolimnetic sediments.

IV. Results

Most lake shore residents and lake users are primarily concerned about trophic state of lakes only during the summer season. This report therefore describes the state of the lakes of the Twin Lakes Watershed in the summer, emphasizing their states before and after aluminum sulfate treatment. The degree of eutrophication is described by the amount of algal biomass, by transparency as an indicator of algal biomass, and by the quantities of phosphorus, particularly total phosphorus. It has previously been demonstrated (Heath and Cooke, 1975; Cooke et al. 1978) that the Twin Lakes are best described as phosphorus-limited lakes, and that algal production should decline as phosphorus concentration declines.

A. Physical-Chemical

1. Temperature and dissolved oxygen.

The distribution of water temperature, dissolved oxygen, and total phosphorus concentration with depth in July of the last pre-treatment year and July, 1978, are compared for the Twin Lakes in Figure 2. The pre- and post-treatment profiles in Dollar Lake were very similar to these.

Thermal stratification usually occurs by early May, followed by a depletion of hypolimnetic dissolved oxygen by mid-June. The amount of dissolved oxygen in Dollar Lake before treatment was very low due to the large algal biomass, greatly reduced transparency, and high respiration rates. Strata below 2 meters were commonly below the dissolved oxygen criteria for game fish. By 1978, the dissolved oxygen situation in Dollar Lake had improved greatly, with a metalimnetic maximum between 3 and 4 meters. A concomitant increase in transparency (see Section B) also occurred. The Twin Lakes were not as eutrophic as Dollar Lake during pre-treatment years and thus had less improvement in dissolved oxygen after treatment.

2. Phosphorus

After thermal stratification occurred and dissolved oxygen in the hypolimnion declines, the concentration of total phosphorus increased rapidly and by mid-summer up to 500 μgP/l in East and West Twin and up to 1000 μgP/l in Dollar could be found before treatment (Figure 2). Based upon the evidence of Stauffer and Lee (1973) and Mortimer (1971), it was our hypothesis that the release of phosphorus from reduced hypolimnetic sediments represented a significant

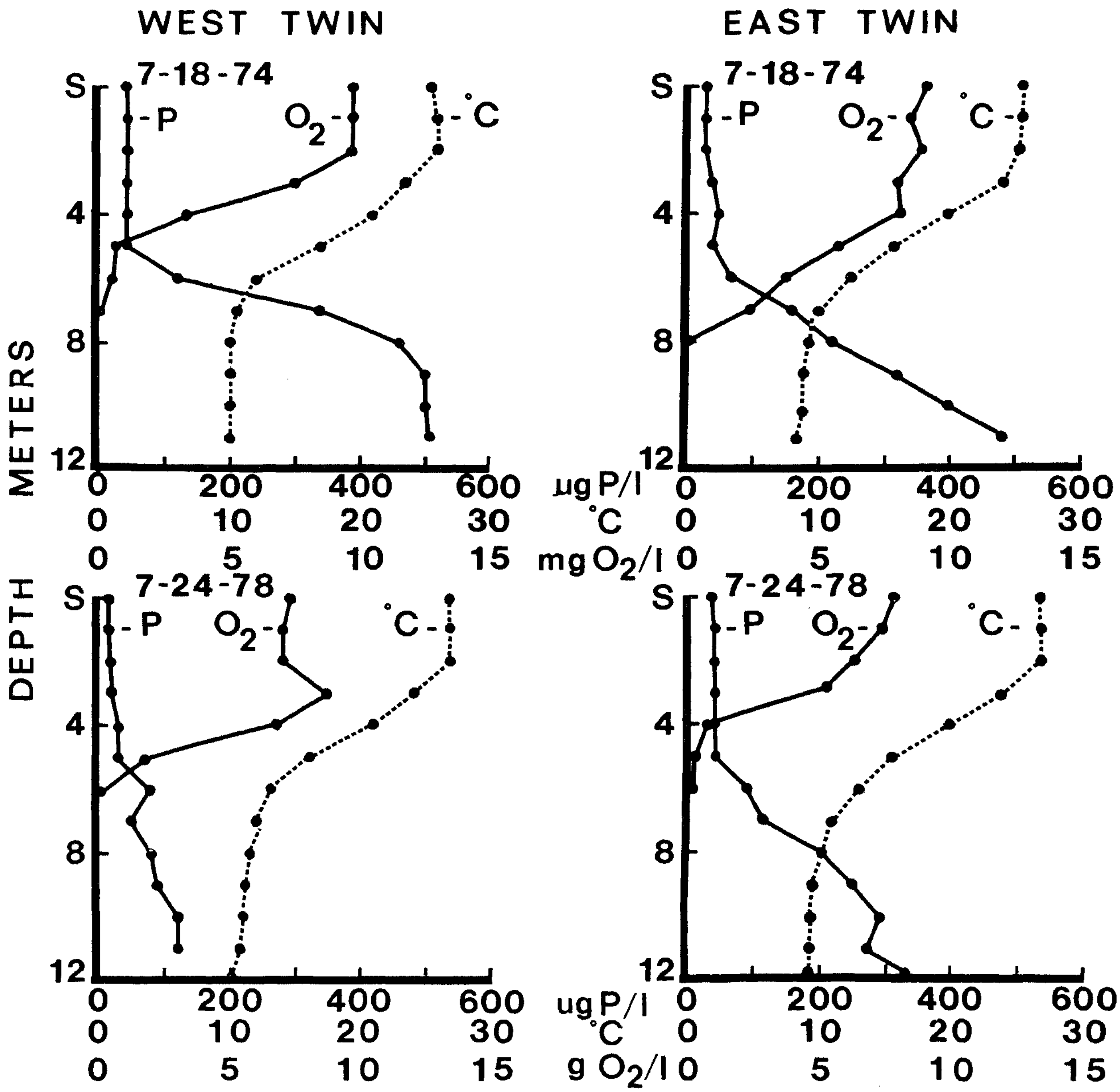


FIGURE 2. Temperature, dissolved oxygen, and total phosphorus in East and West Twin Lakes before and after July 1975 hypolimnetic aluminum sulfate application.

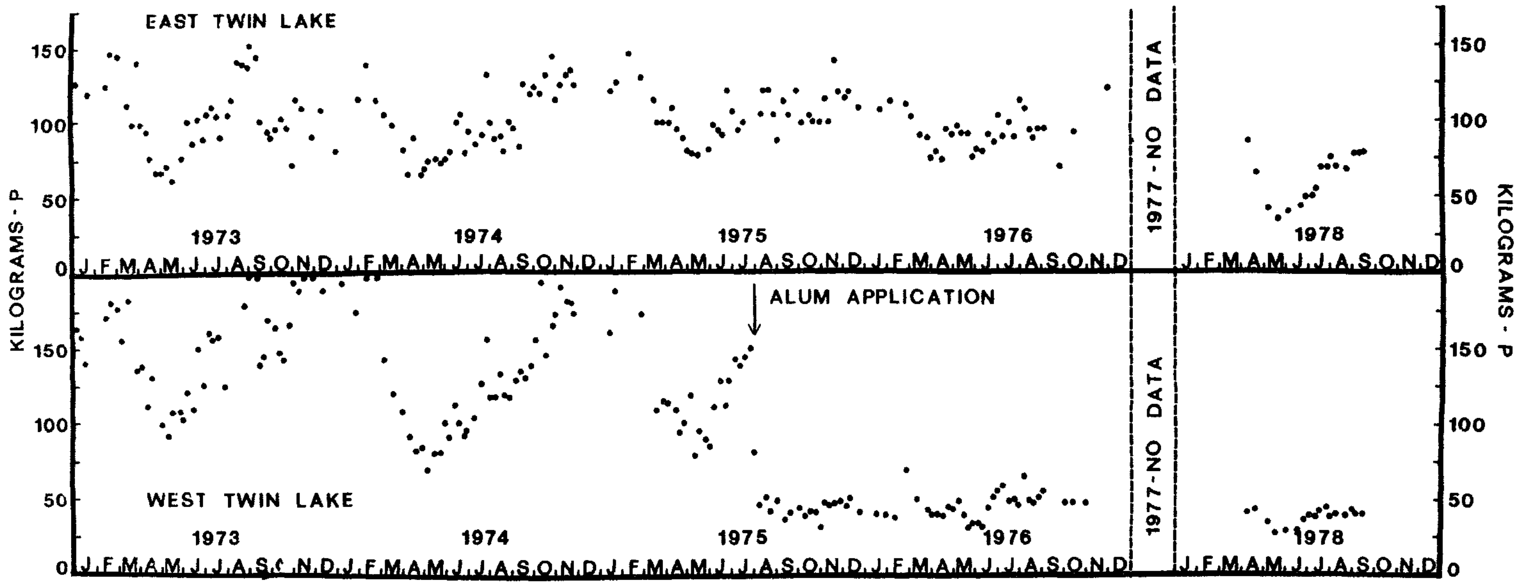


FIGURE 3. Phosphorus content (kilograms-P) of East and West Twin Lake. No samples in 1977.

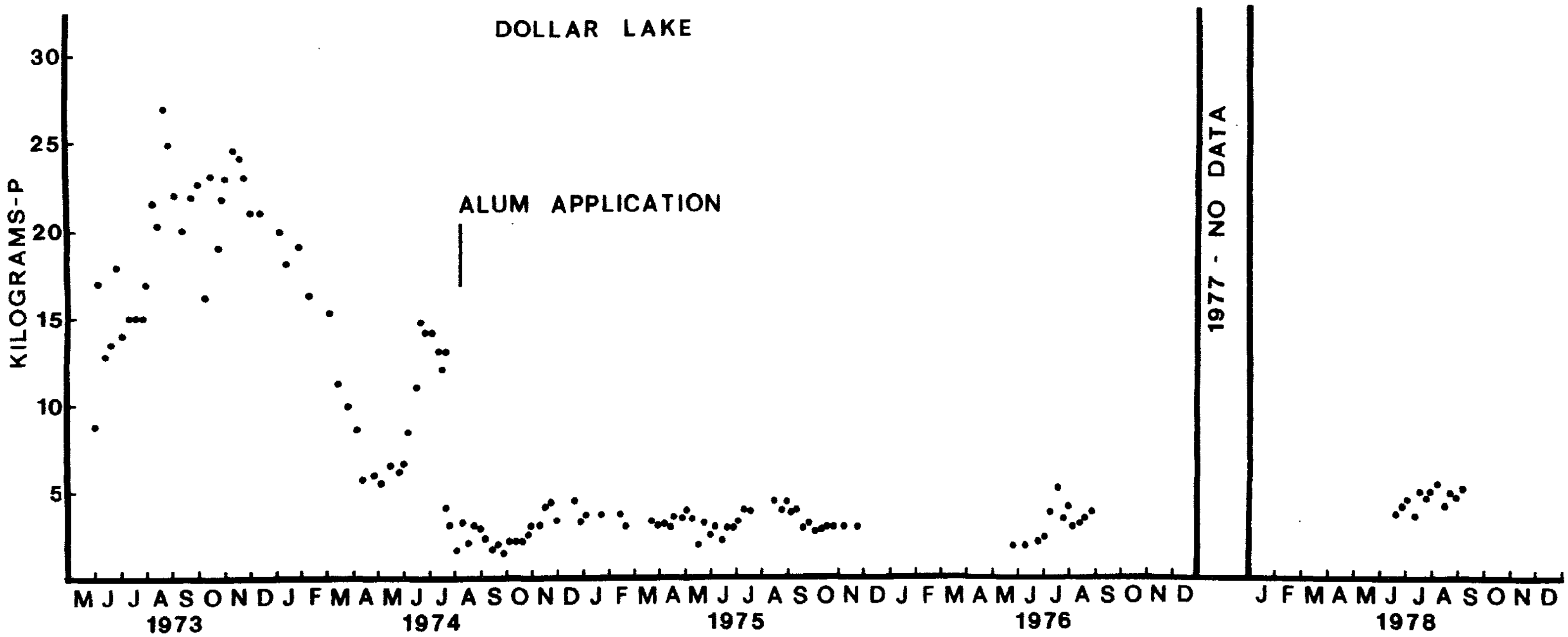


FIGURE 4. Phosphorus content (kilograms-P) of Dollar Lake.
No samples in 1977.

internal source of this element to the epilimnion via vertical entrainment processes. This release was therefore the target of the aluminum sulfate application.

The hypolimnetic total phosphorus concentrations of Dollar and West Twin were immediately lowered after the alum application, and concentration has remained low three and four years after treatment (Figures 2, 3 and 4).

West Twin and Dollar Lakes had higher pre-diversion (1971-72) mean whole lake summer phosphorus concentrations than East Twin, and were more eutrophic. After diversion, phosphorus concentration fell in all lakes, reaching an apparent steady value of about 80 and 73 μgP/l for West and East Twin, respectively, in 1974.

Whole lake mean summer total phosphorus concentration in West Twin was further lowered to about 30 μgP/l after the alum application. Concentration in East Twin declined between 1975 and 1978 to about 45 μgP/l as a result of the low concentration of phosphorus in incoming water from West Twin. In Dollar Lake, alum treatment brought whole lake concentration down from a pretreatment mean of 206 μgP/l to about 40 μgP/l, but concentration increased from 1976 to 1978. These data are summarized in Table 2.

The decline in mean hypolimnetic total phosphorus concentration after the alum application, listed in Table 3, illustrates the effectiveness of the aluminum hydroxide floc in retarding phosphorus release from reduced sediments. Mean West Twin hypolimnetic total phosphorus fell from 400-500 μgP/l to less than 75 μgP/l, a 5-6 fold decrease, and has remained at that level for three years. In Dollar Lake, an equally striking change occurred, but the 1978 mean was nearly double that of 1976 suggesting a decrease in effectiveness of the floc after four years.

The mean epilimnetic total phosphorus concentration declined slightly after diversion and sharply after the alum application (Table 4), and has continued to decline each year since application. The concentration in East Twin was nearly identical to West Twin in 1978.

Table 2

MEAN VOLUME WEIGHTED TOTAL PHOSPHORUS CONCENTRATIONS (μgP/l) IN DOLLAR LAKE AND TWIN LAKES DURING SUMMER

	WEST TWIN	EAST TWIN	DOLLAR
1971	165.22	108.90	
1972	108.92	79.85	
1973	99.81	74.30	206.87
1974	78.75	73.46	
			I 128.40
			II 28.63
			ALL 82.23
1975			
I	80.04		
II	32.20		
ALL	54.97	72.90	38.34
1976	32.41	68.85	36.54
1978	26.31	45.45	50.80

I = Before July Aluminum Sulfate Application
II = After July Aluminum Sulfate Application

Table 3

VOLUME-WEIGHTED MEAN HYPOLIMNETIC
TOTAL PHOSPHORUS CONCENTRATIONS IN
DOLLAR LAKE AND THE TWIN LAKES (µgP/l)

	WEST TWIN	EAST TWIN	DOLLAR
1971	657.31	513.81	
1972	467.44	386.28	
1973	555.35	408.15	464.39
1974	420.50	405.60	
			I 217.45
			II 36.55
1975			All 63.80
I	240.51		
II	38.39		
ALL	134.59	282.69	
1976	75.15	210.75	56.18
1978	64.34	170.79	104.84

I = Before July Aluminum Sulfate Application

II = After July Aluminum Sulfate Application

Table 4

MEAN EPILIMNETIC VOLUME-WEIGHTED TOTAL PHOSPHORUS CONCENTRATIONS IN TWIN AND DOLLAR LAKES (μgP/l)

	WEST TWIN	EAST TWIN	DOLLAR
1971	40.59	30.97	
1972	58.09	44.50	
1973	52.73	37.61	71.08
1974	47.46	44.44	
I*			81.44
II*			24.46
1975			
I#	43.80		
II#	28.93		
ALL	36.01	39.38	24.92
1976	28.26	37.97	26.22
1978	16.11	19.86	20.59

*I = Before July Hypolimnetic-Epilimnetic Alum Application

*II = After Alum Application

#I = Before July Hypolimnetic Alum Application

#II = After Alum Application

The phosphorus content of the lakes, the sum of weekly mean concentration of each stratum multiplied by stratum volume, slowly declined after diversion (see also Cooke et al. 1978 for pre-1973 data) and then sharply after the alum application (Figures 3 and 4). The phosphorus content has remained low throughout the three and four years after application. East Twin, while exhibiting a steady decline in phosphorus content, continued to have the cyclic pattern typical of thermally stratified eutrophic lakes wherein phosphorus content rises during summer and winter, and declines in fall and spring.

3. Internal phosphorus release.

The object of the application of aluminum sulfate to hypolimnetic sediments was to retard the release of phosphorus during the reducing conditions which occur after thermal stratification. It was our hypothesis that this was the main source of internal phosphorus release in dimictic eutrophic lakes.

The calculation of internal phosphorus release is performed by solution of a mass balance equation (4). Since no hydrologic budget has been developed for Dollar Lake, only East and West Twin are described here.

The rate of internal phosphorus release in West Twin, following the applications of a maximum dose of aluminum sulfate to the hypolimnion in July, 1975, declined and has remained much lower than the untreated downstream lake (Table 5). Summer external phosphorus income has remained much more constant and similar over time and between the lakes. Total summer phosphorus income to the treated lake in 1978 was about one-third that of the untreated, even though external income to the untreated lake was very low due to the low concentration in water from West Twin. The aluminum hydroxide floc in West Twin, three years after application, has retained its effectiveness in retarding phosphorus release.

Table 5

NET EXTERNAL, INTERNAL AND
TOTAL PHOSPHORUS INCOME TO THE
TWIN LAKES (mgP/m^2/DAY) DURING SUMMER

WEST TWIN

Year	External	Internal	Total	Days
1972	0.200	2.007	2.207	126
1973	-0.127	2.668	2.541	126
1974	0.435	0.831	1.266	116
1975	NO CALCULATION - ALUM APPLICATION			
1976	0.637	0.689	1.326	77
1978	0.334	0.163	0.497	101

EAST TWIN

Year	External	Internal	Total	Days
1972	-0.054	2.917	2.863	98
1973	0.207	2.804	3.011	112
1974	0.336	0.750	1.086	125
1975	NO CALCULATION - ALUM APPLICATION			
1976	0.663	1.022	1.685	72
1978	0.161	1.351	1.512	101

NOTE: 1. Negative external income is due to negative groundwater income.

2. Days of summer defined as date of spring low phosphorus content to summer high phosphorus content. This interval corresponds to date of thermal stratification in spring and to beginning of destratification in fall.

4. Aluminum, sulfate, alkalinity, pH, and conductance

Aluminum determinations were conducted in 1978 but no conclusions may be drawn about them since our glass-distilled water apparently contained aluminum or some other interference.

After the application of aluminum sulfate in 1975, the hypolimnetic concentration of sulfate increased to about 100 mg SO_4/l (Table 6). Concentration did not increase in the epilimnion and hypolimnetic concentrations returned to normal in 1976 and have remained normal in 1978. Sulfate in the untreated lake did not change.

pH and alkalinity in epilimnetic waters of West Twin were apparently not affected by the treatment (Table 7). pH and alkalinity were depressed in the hypolimnion to 6.0 and 60 mg $CaCO_3$/l respectively after treatment in 1975, but recovered to near-normal values at fall circulation (Cooke et al. 1978). In 1976 and 1978, hypolimnetic pH and alkalinity were normal. The untreated lake exhibited no change (Table 8).

Specific conductance, a measure of the concentration of dissolved ionic matter in the water (Lind, 1974), was depressed slightly in the hypolimnion after the 1975 treatment, but returned to the normal range in 1976 and 1978 (Table 9).

B. Biological

The degree of eutrophy of recreational lakes is perceived by the user in ways related to the amount of biological production, particularly macrophytes and planktonic algae. Macrophytes were not studied during this project, although they are now the primary nuisance in these lakes. Algae were quantitatively examined by determining species identification, cell volume, chlorophyll, and water transparency.

Eutrophic lakes are usually described as lakes with dense "blooms" of algae (cell volume above 3-5 µl/l or chlorophyll above 3-5 mg Chl a/M^3) dominated by

Table 6

MEAN SULFATE (Mg SO_4/l) IN DOLLAR AND TWIN LAKES DURING SUMMER

YEAR	WEST TWIN		EAST TWIN		DOLLAR	
	Epi.	Hypo.	Epi.	Hypo.	Epi.	Hypo.
1972	42.69	29.71	35.98	21.59	-	-
1973	39.82	24.31	36.73	22.30	-	-
1974	38.80	26.02	32.85	25.32	-	-
1975	38.56	53.06	35.44	27.43	-	-
1976	38.13	36.85	22.63	22.72	-	-
1978	30.89	24.27	29.87	20.56	41.02	18.11

Table 7

MEAN pH AND ALKALINITY ($mgCaCO_3/l$)
IN THE EPILIMNION OF DOLLAR AND
TWIN LAKES DURING SUMMER

YEAR	WEST TWIN		EEAST TWIN		DOLLAR	
	pH	ALK.	pH	ALK.	pH	ALK.
1973	7.74	102.06	7.91	95.51	--	--
1974	7.82	91.93	7.70	95.52	--	--
1975	7.88	94.23	8.05	92.94	--	--
1976	7.70	111.44	7.78	103.55	--	--
1978	8.42	96.18	8.29	93.88	8.05	112.08

Table 8

MEAN pH AND ALKALINITY ($mgCaCO_3/l$) IN THE HYPOLIMNION OF DOLLAR AND TWIN LAKES DURING SUMMER

YEAR	WEST TWIN		EAST TWIN		DOLLAR	
	pH	ALK.	pH	ALK.	pH	ALK.
1973	7.32	149.28	7.24	149.70	--	--
1974	7.23	148.14	7.12	142.30	--	--
1975	6.94	100.77	7.53	137.32	--	--
1976	7.22	142.23	7.27	139.19	--	--
1978	7.35	140.04	7.36	127.30	7.30	222.90

Table 9

MEAN SPECIFIC CONDUCTANCE (μmho, 20°c)

OF EAST AND WEST TWIN LAKES DURING SUMMER

YEAR	WEST TWIN		EAST TWIN	
	EPILIM.	HYPOLIM.	EPILIM.	HYPOLIM.
1972	392.94	436.67	352.56	399.31
1973	395.90	425.53	369.93	406.19
1974	378.84	447.21	372.91	427.41
1975	335.61	365.53	339.65	372.09
1976	395.58	447.47	377.18	427.62
1978	367.42	414.35	363.79	394.39

members of the Cyanophyta such as Anabaena, Aphanizomenon, Microcystis, and Oscillatoria, and by low transparency (less than 2 meters). These types of data are compared for 1971-78 to examine the changes after diversion and to assess the effects and duration of the alum application.

1. Phytoplankton species.

Cyanophyta have been the dominants in West Twin, even after the alum treatment, forming up to 80% of the average community in 1978 and more than 99% during the pre-diversion years (Table 10). Only in 1973 was this changed, apparently due to a massive application of copper sulphate. East Twin has also been dominated by blue-green algae until 1978 when the dinoflagellate Ceratium hirundinella became the dominant.

The percent of the phytoplankton community dominated by Cyanophyta varied over the summer in the post-diversion and post-treatment years, particularly in 1976 and 1978. In 1976, the lakes behaved in opposite ways, with East Twin having blue-green dominance in the early summer, West Twin in late summer. In 1978 both lakes were dominated by blue-greens by September (Table 11).

The identification of the dominant blue-green alga was very constant between lakes until the post-treatment years when Aphanizomenon in 1976 was the East Twin dominant but West Twin shifted from Anabaena spiroides in June to Aphanizomenon in July to Anabaena limnetica in August. In 1978, Microcystis aeruginosa was the dominant in East Twin except in August when a large bloom of Oscillatoria rubescens occurred. West Twin again shifted from Microcystis aeruginosa in June to a new dominant Lyngbya Birgei, then to Anabaena limnetica (Table 12).

In contrast to pre-treatment years, the phytoplankton community of West Twin in 1976 and 1978 and East Twin in 1978 had significant populations of diatoms, dinoflagellates, and green algae. Species of Cyclotella, Ceratium, Sphaerocystis, and Phacotus became more important, even though most of the cell volume of the phytoplankton was that of blue-greens.

Table 10

MEAN PERCENT PHYLA AND SPECIES COMPOSITION
AUGUST SURFACE (0.1 M) SAMPLES*

WEST TWIN

	1971	1972	1973	1974	1975	1976	1978
1. Blue-Greens	99.9(1)	98.1(2)	39.5(2)	93.8(1)	97.9(1)	84.8(1)	78.9(1)
2. Diatoms	0.1	1.2(2)	43.3(2)	3.8(2)	0.8(2)	2.3(3)	7.4(2)
3. Chlorophyta	0	0.1(1)	17.2(1)	0.2(1)	1.1(1)	0.1(1)	0.6(2)
4. Dinophyceae	0	0	0	2.4(1)	0.2(1)	12.9(1)	10.6(1)
MEAN CELL VOL. (µl/l.)	17.88	3.27	0.12	4.68	5.24	2.16	0.72

EAST TWIN

	1971	1972	1973	1974	1975	1976	1978
1. Blue-Greens	88.8(1)	99.2(2)	97.5(2)	88.9(1)	97.0(1)	54.6(2)	29.7(7)
2. Diatoms	11.3(1)	0.2(2)	2.5(1)	8.8(1)	1.0(1)	40.0(3)	16.2(2)
3. Chlorophyta	0	0	0	0	0	0.5(1)	1.2(2)
4. Dinophyceae	0	0.7(1)	0	0	1.9(1)	4.9(1)	49.9(1)
MEAN CELL VOL. (µl/l.)	3.03	4.24	7.00	3.84	7.88	1.76	0.16

<u>Blue-Greens</u>
1. Anabaena limnetica
2. Aphanizomenon flos-aquae

<u>Diatoms</u>
1. Stephanodiscus
2. Cyclotella
3. Fragilaria

<u>Chlorophyta</u>
1. Sphaerocystis
2. Phacotus

<u>Dinophyceae</u>
1. Ceratium

*Numbers in parentheses refer to dominant species.

Table 11

BLUE GREEN ALGAE - PERCENT OF TOTAL SURFACE CELL VOLUME IN TWIN LAKES

	June		July		August		September	
	WTL	ETL	WTL	ETL	WTL	ETL	WTL	ETL
1971	99.7	76.4	98.6	83.2	99.9	88.8	99.2	94.0
1972	19.0	98.9	37.9	98.2	98.1	99.2	99.5	97.1
1973	52.5	92.8	22.0	90.9	39.5	97.5	98.3	98.7
1974	68.1	91.5	89.0	84.1	93.8	88.9	99.4	96.2
1975	77.7	92.9	96.0	93.6	97.9	97.0	98.0	95.2
1976	26.9	79.7	78.9	69.7	84.8	54.6	--	--
1978	44.6	11.0	61.2	8.0	78.9	29.7	81.0	79.5

WTL = West Twin Lake
ETL = East Twin Lake

Table 12

DOMINANT BLUE-GREEN ALGA IN THE TWIN LAKES

	June		July		August		September	
	WTL	ETL	WTL	ETL	WTL	ETL	WTL	ETL
1971	2	2	2	2	2	2	2	2
1972	5	3	3	3	3	3	3	3
1973	3	3	3	2	3	3	3	3
1974	2	2	2	2	2	2	2	2
1975	2	2	2	2	2	2	2	2
1976	1	3	3	3	2	3	-	-
1978	4	4	6	4	2	7	2	4

1 = *Anabaena spiroides*

2 = *Anabaena limnetica*

3 = *Aphanizomenon flos-aquae*

4 = *Microcystis aeruginosa*

5 = *Anabaena flos-aquae*

6 = *Lyngbya Birgei*

7 = *Oscillatoria rubescens*

In Dollar Lake (Kennedy, 1978), blue-greens were the sole dominants in 1973 (Anabaena limnetica and Microcystis sp.), with blooms up to 31 µl/l and a mean of 11.6 µl/l. After the 1974 treatment, Aphanizemenon remained as the dominant but total cell volume was low (1.0 µl/l). In 1975 and 1976 total cell volume remained below 2.0 µl/l. Aphanizomenon was the 1975 dominant, but in 1976, as in West Twin in 1976, greens, diatoms and dinoflagellates were much more abundant. In 1978 mean cell volume was 1.47 µl/l at the surface, with 97% of this due to blue-green algae. Oscillatoria rubescens was the 1978 dominant and Ceratium the sub-dominant. Diatoms and greens were rare and represented by very few species.

2. Cell volume in Twin Lakes.

Mean summer cell volume (Table 13) was very similar between lakes before treatment, and much lower but still similar after treatment. The mean cell volume after treatment was 3-4 fold less than before. Dollar Lake also experienced a sharp reduction in cell volume after alum treatment (see above).

In the pre-treatment years cell volume was usually somewhat higher in East Twin over the summer, presumably due to the use of copper-containing herbicides in West Twin, which probably reduced the amount of large celled blue-greens. After treatment, cell volume was always less over the summer months in East Twin, particularly in 1978 (Table 14).

3. Chlorophyll

Mean summer chlorophyll, a measure of algal biomass, did not change greatly after diversion except in West Twin in 1973 when copper was used very heavily. After the alum treatment chlorophyll declined to levels about one-third of the pre-treatment means (Table 15). Chlorophyll was very high in Dollar Lake before treatment, reaching values near 100 mg Chl a/M^3 in 1974. In 1975-78, chlorophyll was half or less than pre-treatment values.

4. Transparency

Water transparency, a measure of visibility, is proportional to algal biomass as measured by chlorophyll, and is the best indicator of lake trophic

Table 13

MEAN CELL VOLUME ($\mu l/l$) IN SURFACE PHYTOPLANKTON SAMPLES IN EAST AND WEST TWIN LAKES (JUNE-SEPTEMBER)

	YEAR	WEST TWIN	EAST TWIN
	1971	13.41	2.42
	1972	2.50	3.79
	1973	0.88	3.86
	1974	3.37	3.05
	1975	4.28	4.72
	1976	1.23	1.32
	1978	0.78	0.66
PRE-TREATMENT	MEAN (1971-75)	4.89	3.57
POST-TREATMENT	MEAN (1976-78)	1.01	0.99

Table 14

MEAN CELL VOLUME OF TWIN LAKES
SURFACE PHYTOPLANKTON

Date	June WTL	June ETL	July WTL	July ETL	August WTL	August ETL	September WTL	September ETL
1971	12.14	1.83	12.81	3.37	17.88	3.03	10.80	1.45
1972	0.46	3.79	1.48	3.46	3.27	4.24	4.80	3.66
1973	1.23	1.99	0.35	4.08	0.12	7.00	1.80	2.37
1974	2.22	2.43	3.68	2.50	4.68	3.84	2.89	3.43
1975	3.81	4.19	4.87	2.04	5.24	7.88	3.20	4.78
1976	0.14	1.30	1.40	0.91	2.16	1.76	--	--
1978	0.27	1.97	0.83	0.73	0.70	0.16	1.28	0.16
Pre-Treatment Mean (1971-74)	4.01	2.51	4.58	3.35	6.49	4.53	5.07	2.73
Post-Treatment Mean (1976-78)	0.21	1.64	1.12	0.82	1.43	0.96	1.28	0.16

WTL = West Twin Lake
ETL = East Twin Lake

Table 15

MEAN SUMMER (JUNE-SEPTEMBER) SURFACE CHLOROPHYLL CONCENTRATIONS (MgChla/M^3) IN EAST AND WEST TWIN AND DOLLAR LAKES

	YEAR	WEST TWIN	EAST TWIN	DOLLAR
	1971	44.67	12.41	---
	1972	15.40	20.02	---
	1973	11.80	14.99	40.56
	1974	23.63	17.91	25.50
	1975	16.55	26.99	11.15
	1976	7.73	6.07	10.04
	1978	6.93	6.15	8.31
PRE-TREATMENT	MEAN (1971-75)	22.41	18.46	40.56(1973)
POST-TREATMENT	MEAN (1976-78)	7.33	6.11	9.83(1975-78)

state from the user's viewpoint. In the Twin Lakes, transparency was often good (greater than 2.5 M) due to the use of copper to destroy blue-greens. Algicides were used sparingly after 1973 and transparency values again fell to pre-diversion and early post-diversion levels. After the 1975 treatment, mean transparency improved, particularly in 1978. Transparency was very low in Dollar Lake but improved sharply after the 1974 alum application to a 1978 summer mean of 2.39 meters (Table 16).

5. Quantitative changes in trophic state

Sharp divisions between oligotrophic-mesotrophic-eutrophic lakes have been difficult to define on the basis of quantities of indicator items such as cell volume, rates of oxygen depletion, or concentration of nutrients. Recognizing this fact, Carlson (1977) developed a trophic state index (TSI), in which a number is assigned to a lake based upon the amount of algal biomass as measured by transparency or chlorophyll, or by the concentration of total phosphorus which is directly related to biomass. The index is scaled from 0, the highest recorded water transparency and lowest algal biomass, to about 110, which seems to include the highest algal biomass recorded and lowest transparency (about 3 cm). The scale is constructed so that each increase of 10 units represents a doubling of algal biomass. Thus a lake with an index of 65 has twice as much algal biomass as one with an index of 55 (Table 17).

Carlson (1978) reviewed the uses of trophic state indicators in the literature and found that the upper limits of oligotrophy and lower limits of eutrophy were remarkably similar among various authors. Their limits, when tranformed to Carlson TSI units, are 41 ± 5.75 (1 S.D.) to 51 ± 7.61 (1 S.D.). These boundaries will be used in this report.

The mean summer TSI for the Twin Lakes and Dollar Lake remained in the eutrophic range and were rather constant from one year to the next before the aluminum sulfate treatment. It should be noted that the TSI for transparency was

Table 16

MEAN TRANSPARENCY (METERS) OF TWIN AND DOLLAR LAKES DURING JUNE-SEPTEMBER

YEAR	WEST TWIN	EAST TWIN	DOLLAR
1971	1.04	2.51	--
1972	2.62	1.98	--
1973	2.65	3.61	0.77
1974	1.84	1.57	0.79
1975	1.51	1.70	1.91
1976	2.51	1.62	2.31
1978	2.53	2.65	2.39

Table 17

RELATIONSHIP BETWEEN CARLSON
TROPHIC STATE INDEX VALUES AND
PARAMETERS USED TO MEASURE IT
(FROM CARLSON, 1977)

TSI	SECCHI DISC (M)	SURFACE PHOSPHORUS (μgP/l)	SURFACE CHLOROPHYLL (mg/M^3)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.06	768	1183

low for most pre-treatment years in the Twin Lakes, particularly West Twin, due to the heavy use of copper sulfate which increased transparency by killing blue-green algae but did not affect the cause of the high algal biomass, the high concentration of phosphorus. Often, chlorophyll would remain high after a copper treatment due to the increase in abundance of unaffected smaller sized species. The TSI value for total phosphorus in the pre- and post-alum treatment years is probably the best indicator of trophic state in these lakes (Table 18, Figure 5).

The trophic state of the Twin Lakes has improved to a mesotrophic state after the aluminum sulfate application and has remained in this state three and four years after treatment. East Twin was in the eutrophic category in 1976, but by 1978, after two years of receiving water low in phosphorus from West Twin, also became mesotrophic. Dollar Lake exhibited the greatest change in trophic state after alum application, with a 3-fold decrease in mean summer surface algal biomass, and is now mesotrophic as well. (Table 18).

6. Impact of alum application on zooplankton

What effects on the biota, other than the desired reduction in algal standing crop, may occur after a lake has received a hypolimnetic treatment with a maximum dose of aluminum sulfate? The presence of free or residual dissolved aluminum (RDA) can be acutely toxic to fish and microcrustacea (Freeman and Everhart, 1971; Biesinger and Christensen, 1972; Wilbur, 1974). West Twin was treated with a dose of alum which was designed to keep RDA below 50 µgAl/l, a dose which Freeman and Everhart (1971) found to be safe for trout. Petersen et al. (1974) reported that at a dose of 40 µg Al/l, survival of Daphnia magna was between 90 and 100%. Thus laboratory tests predict that a dose of 50 µg Al/l or less should not bring about acute toxicity problems. However, the response of a community or a lake, the actual levels of biological organization to which the alum is applied, might not be predicted from tests at the organism and species population levels.

Table 18

MEAN (MAY-SEPTEMBER) CARLSON TROPHIC STATE INDEX
(CALCULATED FROM SURFACE MEASUREMENTS)

	WEST TWIN			EAST TWIN			DOLLAR		
	TRANS	CHL	TP	TRANS	CHL	TP	TRANS	CHL	TP
1968		NO DATA			NO DATA		66.34	—	—
1969	50.00			51.61				NO DATA	
1971	61.05	68.10	57.58	50.44	56.34	53.68		NO DATA	
1972	48.30	57.94	62.75	52.78	60.27	58.91		NO DATA	
1973	43.17	52.77	61.36	48.96	56.96	56.48	63.77	66.92	64.31
1974	49.86	60.56	59.84	50.51	58.24	58.89	SEE KENNEDY (1978)		
1975	51.44	58.58	55.85	51.93	62.30	57.14	50.68	54.26	50.22
1976	46.72	49.78	52.36	51.44	52.40	56.62	47.94	53.23	50.65
1978	46.38	49.89	44.25	45.51	49.70	47.27	47.75	51.80	47.79
1971-1974	50.48	59.84	60.38	50.86	57.95	56.99	63.77*	66.92*	64.31*
1976-1978	46.55	49.84	48.31	48.48	51.05	51.95	48.79**	53.10**	49.55**
DECREASE IN ALGAL BIOMASS 1971-74 vs. 1976-1978	0.79	2.00	2.41	0.48	1.38	1.01	3.00	2.76	2.95

* = 1973 DATA ONLY
** = 1975-1978 DATA

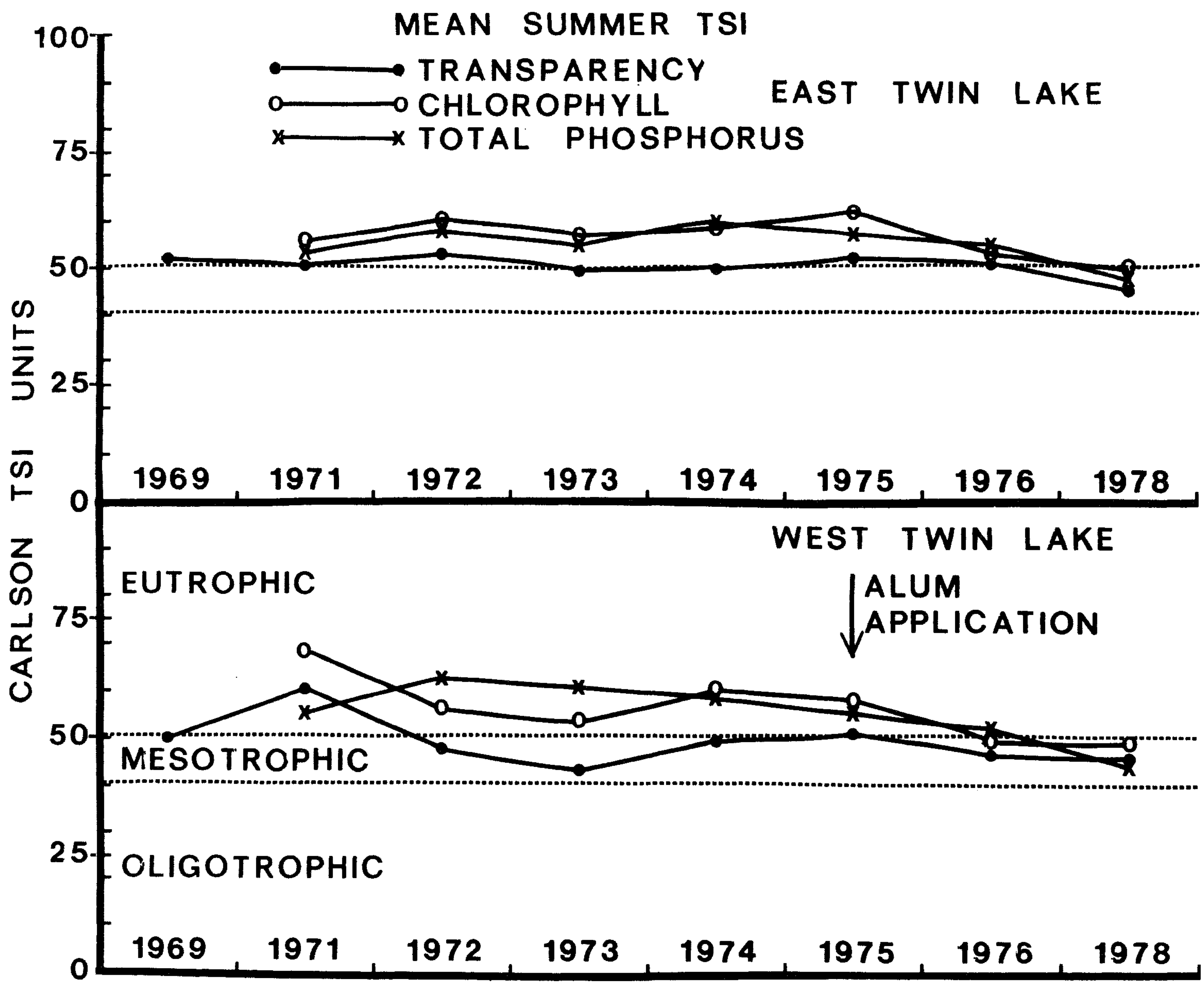


FIGURE 5. Changes in mean summer Carlson (1977) Trophic State Index numbers for East and West Twin Lakes.

The response of the pelagic microcrustacea community to the alum treatment was examined by comparing Shannon and Simpson species diversities and the Pinkham and Pearson Coefficient of Similarity (see methods) for the aggregated (13-17 samples per lake) summer zooplankton samples of 1969 (Heinz, 1971), 1976 (Cooke and Myers, unpub.) and 1978 (Moffett, 1979).

Residual dissolved aluminum concentration in 1975 and 1976 was below the limits of detection (less than 20 µg Al/l) in West Twin. In 1978, interferences with the test prevented an accurate measurement of concentration, but it appeared to always be below 20 µg Al/l. Thus RDA appeared to be less than the levels which laboratory tests suggest might bring about toxic conditions.

The Shannon species diversity of the planktonic microcrustacea of West Twin declined significantly ($p < .05$) after the hypolimnetic aluminum sulfate application, when aggregate diversities of 1976 and 1978 are compared to West Twin aggregate 1969 diversities or to diversities of all years in East Twin. Aggregate Shannon diversity of East Twin samples increased between 1969 and 1978, although not significantly ($p < .05$) (Table 19).

The calculation of a Simpson diversity index for the aggregate samples shows that West Twin microcrustacea exhibited more dominance than East Twin after the treatment (the index becomes 1.0 when only one species is present), but dominance was identical between the lakes before treatment (Table 19).

The Pinkham and Pearson (1976) Coefficient of Similarity, which compares samples for both presence or absence of species and their abundance, indicates that the lakes became sharply dissimilar in 1976 after the treatment, and have become somewhat more similar in 1978. Both lakes, when compared to themselves, were very dissimilar in 1976 compared to 1969, and have regained some similarity to the pre-treatment year in 1978, particularly East Twin (Table 19).

Table 19

SPECIES DIVERSITY AND COEFFICIENT OF SIMILARITY IN AGGREGATED MICROCRUSTACEA SAMPLES FROM EAST AND WEST TWIN LAKES

A. SHANNON H' AGGREGATE DIVERSITIES

	WEST TWIN	EAST TWIN
1969	1.84	1.76
1976	1.39	1.78
1978	1.55	1.94

B. "T" TEST (HUTCHESON, 1970) FOR COMPARISON OF AGGREGATE DIVERSITIES (* = SIGNIFICANTLY DIFFERENT AT 5% LEVEL, N.S. = NOT DIFFERENT, - = TEST NOT APPROPRIATE)

	WTL '69	WTL '76	WTL '78	ETL '69	ETL '76	ETL '78
WTL '69	-	*	*	N.S.	-	-
WTL '76	*	-	N.S.	*	*	-
WTL '78	*	N.S.	-	-	-	*
ETL '69	N.S.	-	-	-	N.S.	N.S.
ETL '76	-	*	-	N.S.	-	N.S.
ETL '78	-	-	*	N.S.	N.S.	-

C. SIMPSON DIVERSITY

	WEST TWIN	EAST TWIN
1969	0.76	0.79
1976	0.80	0.72
1978	0.83	0.72

D. PINKHAM AND PEARSON COEFFICIENT OF SIMILARITY

1. BETWEEN LAKES

1969	0.55
1976	0.30
1978	0.44

2. WITHIN LAKES, BETWEEN YEARS

	1969-76	1969-78	1976-78
WEST	0.14	0.31	0.31
EAST	0.11	0.21	0.41

V. Discussion

The objective of the Twin Lakes Project was to develop the methodology and to test the short and longer term effectiveness of aluminum sulfate as a lake restoration technique. Based upon the conclusions of Mortimer (1971) and Stauffer and Lee (1973) and others, it was our hypothesis that lake recovery after nutrient diversion would be slower than expected since eutrophic lakes appear to have a significant internal source of phosphorus, the reduced hypolimnetic sediments. Therefore, as much alum as possible, within the limits prescribed by laboratory tests for toxicity to fish (Freeman and Everhart, 1971; Wilbur, 1974) was applied to the hypolimnion of West Twin Lake in 1975 to retard or stop the phosphorus release. Since the lakes had been shown to be phosphorus-limited it was believed that recovery, as evidenced by indicators of algal biomass, would increase. A pilot test of the method was made to hypereutrophic Dollar Lake in 1974, following extensive laboratory and field studies to ascertain dose characteristics, effectiveness, and toxicity (Wilbur, 1974; Kennedy, 1978). The reader is urged to consult Cooke et al. (1978) for a review of these studies, and especially Kennedy (1978) for a discussion of the biological and chemical basis for dose, methods of application, and the results of the Dollar Lake treatment.

The Twin Lakes experiment with aluminum sulfate is the first in which a step-by-step approach was taken to provide a scientific basis for dose to test for toxicity, and to apply a maximum dose of alum specifically to the sediments for the purpose of providing long-term control of phosphorus release. Unlike many earlier alum treatments (see Dunst et al. 1974; Peterson et al. 1974 for reviews), this treatment was not directed at removal of phosphorus from the water column, a procedure which adds only enough alum to remove a few kilograms and thus gives only short-term control to phosphorus release from the sediments. Instead it was designed for longer-term control of phosphorus concentration.

The 1976 and 1978 evidence from lake monitoring supports the conclusion that the alum application to the hypolimnion sharply retarded internal phosphorus release, that phosphorus concentration in the epilimnion and the whole lake fell as a result of the treatment, and that both treated lakes are now mesotrophic rather than eutrophic. The monitoring has revealed that the treated lakes, and later the downstream untreated lake, have epilimnetic phosphorus concentrations less than half that of pre-treatment years, very low cell volumes with an increase of phyla other than Cyanophyta, low chlorophyll, and higher transparency. A quantitative index (Carlson, 1977) places all lakes in a mesotrophic range.

The treatment appears to have longevity and the lakes have improved steadily since treatment, presumably as phosphorus is flushed out of them and little new phosphorus enters from the treated sediments or from the land or upstream lakes, in the case of East Twin. The phosphorus concentration in Dollar Lake in 1978 was higher than 1976 and blue-green algae were very dominant, suggesting a possible decline in effectiveness of the aluminum hydroxide after four years. It must be recalled however that Dollar Lake may have a much larger water residence time, allowing accumulation of phosphorus from income to occur, and that the lake was hypereutrophic (TSI above 66 before treatment) with 3 times the algal biomass of the Twin Lakes.

The results of the application of aluminum sulfate to the hypolimnion have demonstrated that internal phosphorus release occurs from compartments other than the reduced hypolimnetic sediments (Cooke et al. 1977; Cooke et al 1978; Table 5), since aluminum-treated sediments release very little phosphorus (Kennedy, 1978). These other sources may be groundwater flows, fish (La Marra, 1975), macrophytes (McRoy et al. 1972) or littoral sediments (Wetzel, 1975).

Alum application may therefore be more effective in stratified lakes in which basin morphometry does not permit extensive littoral areas. The role of the littoral community in lake nutrient dynamics is poorly understood (Wetzel, 1975). Future lake restoration research must be directed towards a better understanding of this community since it may, itself, be the more significant nuisance to lake users, but also may be a significant regulator of nutrient concentration in the open water through nutrient release and through the production of detritus which later brings about greatly lowered redox potentials (Rich and Wetzel, 1978).

While the alum treatment did not lead to permanent adverse changes in those aspects of the water chemistry which would be most likely to change (pH, alkalinity, sulfate, conductance, aluminum), the treatment had a pronounced effect on the pelagic microcrustacea community, reducing its species diversity. Cooke and Myers (unpub.) have suggested that this was probably not due to direct toxicity, since aluminum concentration (RDA) remained below toxic limits as designed, but to either effects on resting stages in hypolimnetic sediments or to changes in food supply as evidenced by the increase in micro-algae. It is important to note that these changes in diversity were not predicted by laboratory toxicity studies. This is as expected since the alum was not applied to the species population or organism levels of organization but to an ecosystem. This observation strongly suggests caution in the use of laboratory studies on individuals or populations as a basis for inferring the behavior of more complex systems. The cause of the diversity change is not now understood and deserves careful attention since it indicates a more severe perturbation than was shown by other studies.

The results of this research will be of direct usefulness to the lake users of Ohio and elsewhere. Lakes which are eutrophic may be improved by diversion of nutrients. This is especially shown by the response of East Twin to the income of phosphorus-poor water from West Twin. In many lakes without the benefit of flushing with nutrient-poor water, such as Dollar and West Twin Lakes, the use of aluminum sulfate to control phosphorus release from hypolimnetic sediments, may bring a marked improvement, and will clearly provide much longer control of nuisance algae blooms than the repeated and costly short-term solution of herbicides. The alum technique however may have more impact and longer lasting effects in lakes with small littoral development.

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